DESIGN AND FABRICATION OF SENSORS ON FIBERS

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Overview

- **OBJECTIVE**
  - **Develop *Smart Materials* through devices / sensors on fibers**
- **APPROACH**
  - **Materials and fabrication methods**
  - **Connectors and traces**
  - **Sensor design**
    - Flow monitoring of Micro-flow
    - Strain sensor
    - Temperature (thermocouple) sensor
    - Others
  - **Device design**
    - Diode
    - Transistors
    - Microprocessors

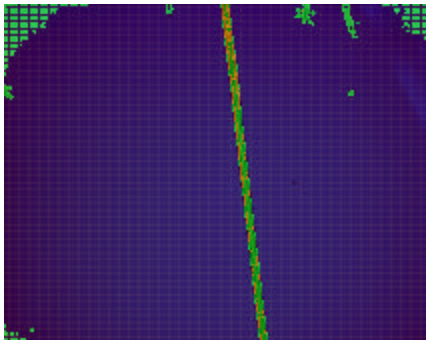
Challenges

- **Connections**
  - **External**
  - **Internal**
- **Miniaturization of Sensors and Devices**
  - **New concept of circular masks for printing on fibers**
- **Compatibility**
  - **Fiber-Device Interface**
  - **Device Durability**
    - Composite Processing
    - In-Service (Strain, Load, Fatigue, Temperature, etc.)
- **Potential for Scale-up**
  - **Continuous processing of fibers**
  - **SMART preforms**

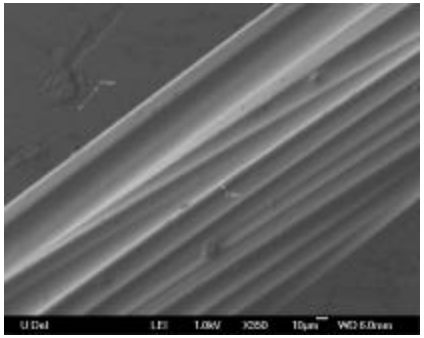
Materials and Methods

- **Fibers**
  - **E-glass (diameter: 14μm)**
  - **Kevlar (diameter: 12μm)**
  - **Optical fiber (diameter: 250μm)**
- **Photoresist**
  - **Photosensitive polymeric material sensitive to i-line (365nm) and h-line (405nm) UV radiation**
- **Limitations of working with a fiber tow**
  - **Photoresist flows through gap between fibers, causes very uneven surfaces**

E-glass

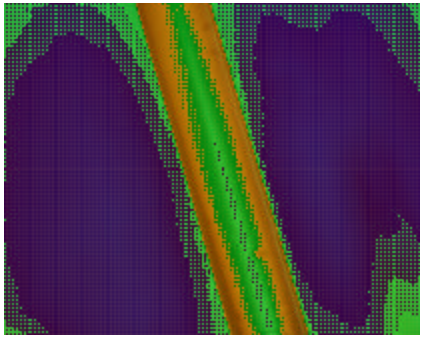


S2-glass



Kevlar fiber tow

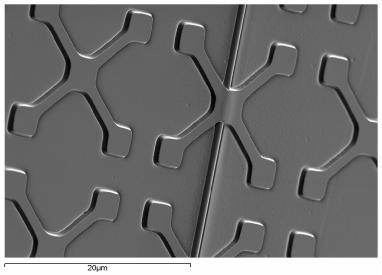
Fiber tow of approximately 50 fibers coated with photoresist



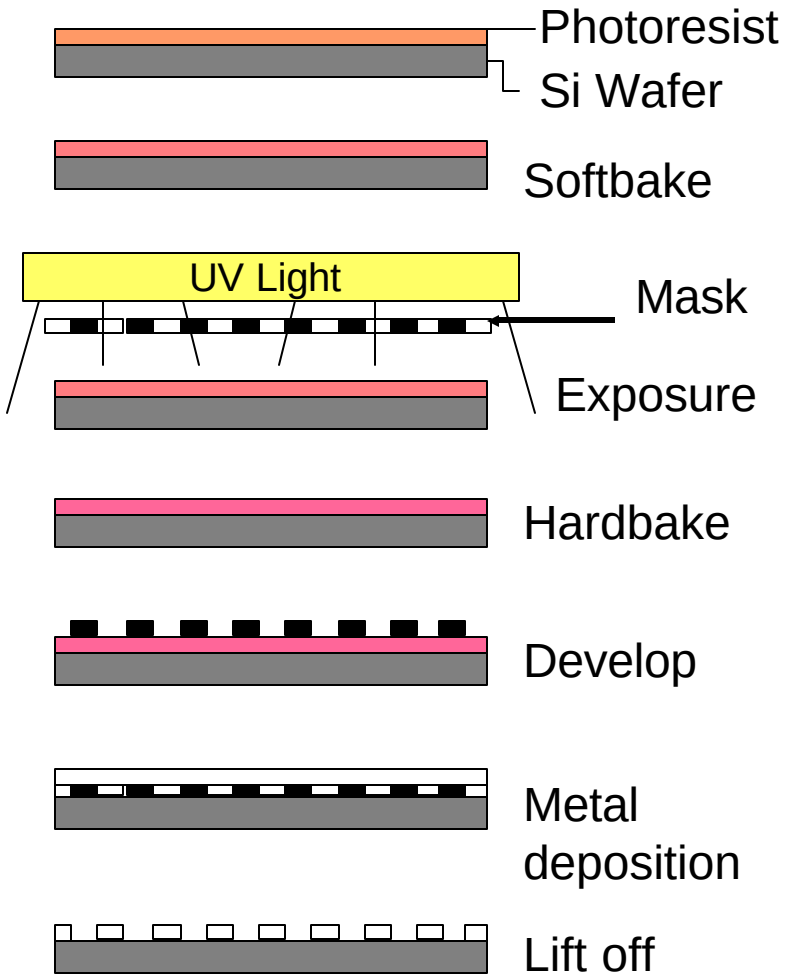
Fiber optic

Review: Micro-Device Fabrication

- **Fabrication steps**
  - **Mask**
  - **Lithography**
    - Coat with photoresist
    - Softbake
    - Exposure to UV light
    - Hardbake (in some cases)
    - Develop
  - **Metal Deposition**

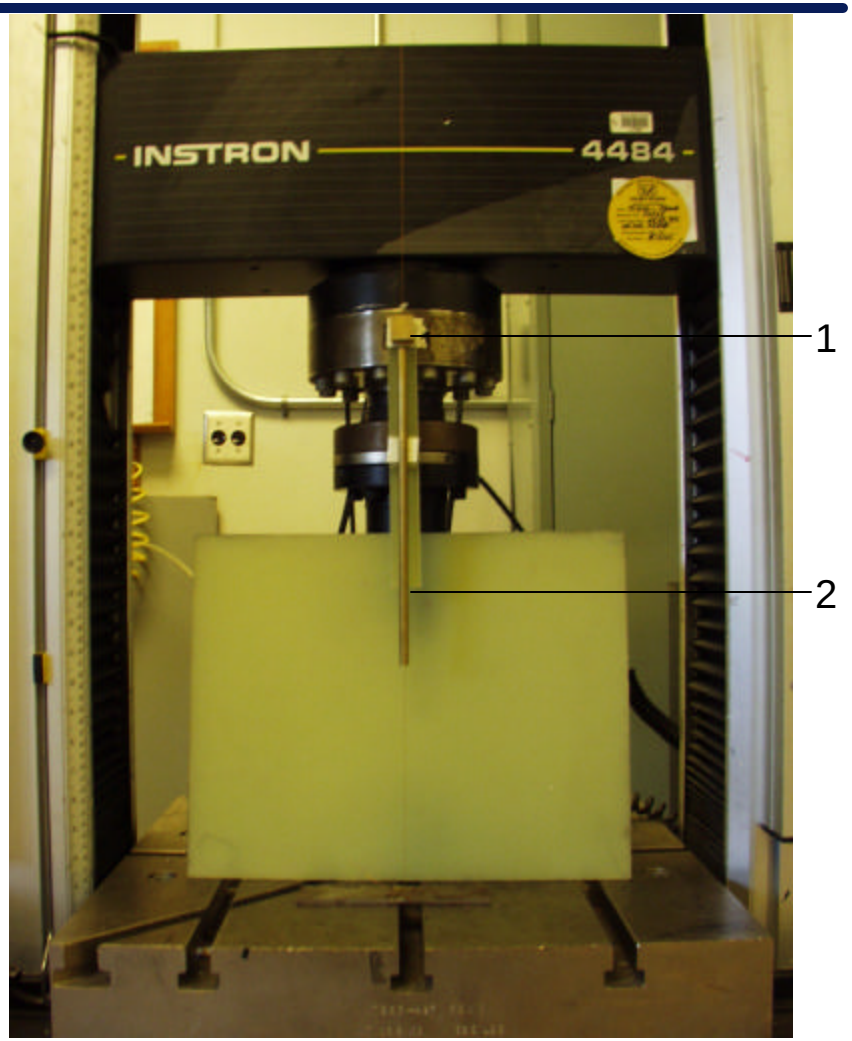


  - **Lift-off (of unwanted metal)**



New Continuous Photoresist Coating Process

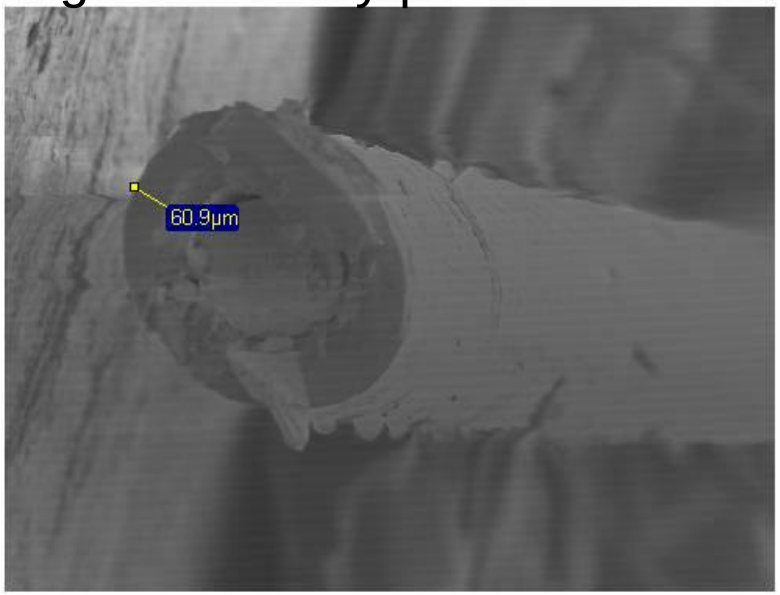
- **Method of coating fiber with photo-resist**
  - **Cross-head frame (Instron)**
  - **Modification from standard spin coating system**
  - **Uniformity of layer:**
    - Viscosity of photoresist material (lower viscosity favored)
    - Speed
- **1- Die containing photoresist**
- **2- cylindrical heater element for immediate softbake following coat**



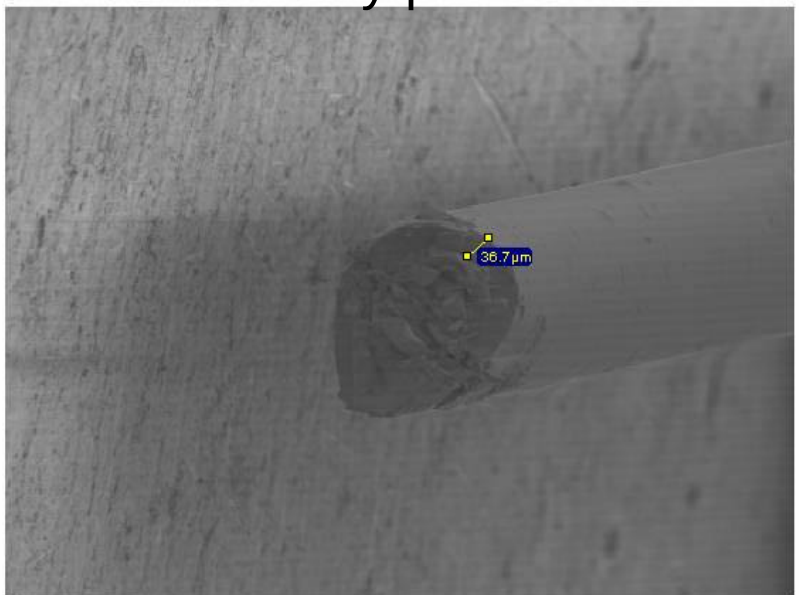
Setup developed for coating

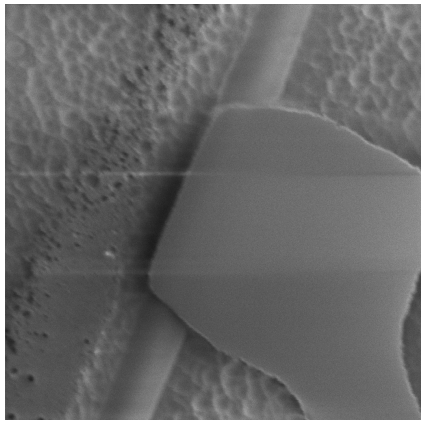
Continuous Coating Process

Higher viscosity photoresist



Lower viscosity photoresist

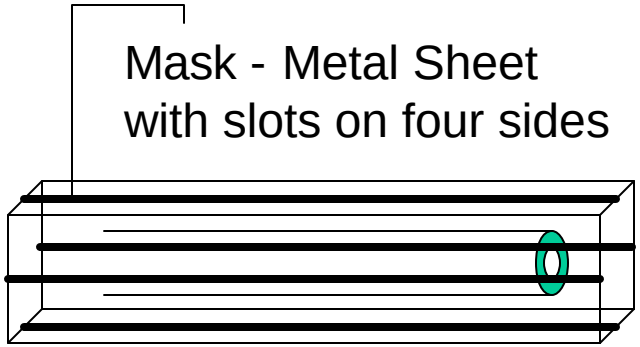




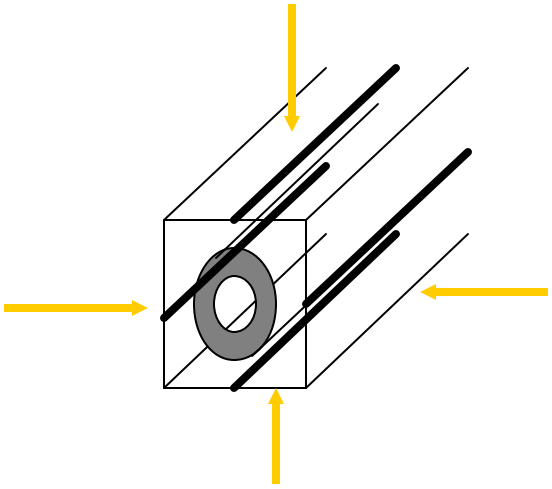
E-glass Fiber coated with photoresist by conventional spin-coat method (flat pattern)

Future Work: Continuous Masking of Photoresist for Traces

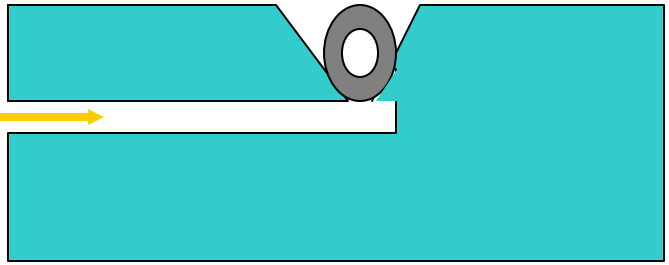
➢ **Near term future work: Implementation of continuous masking**



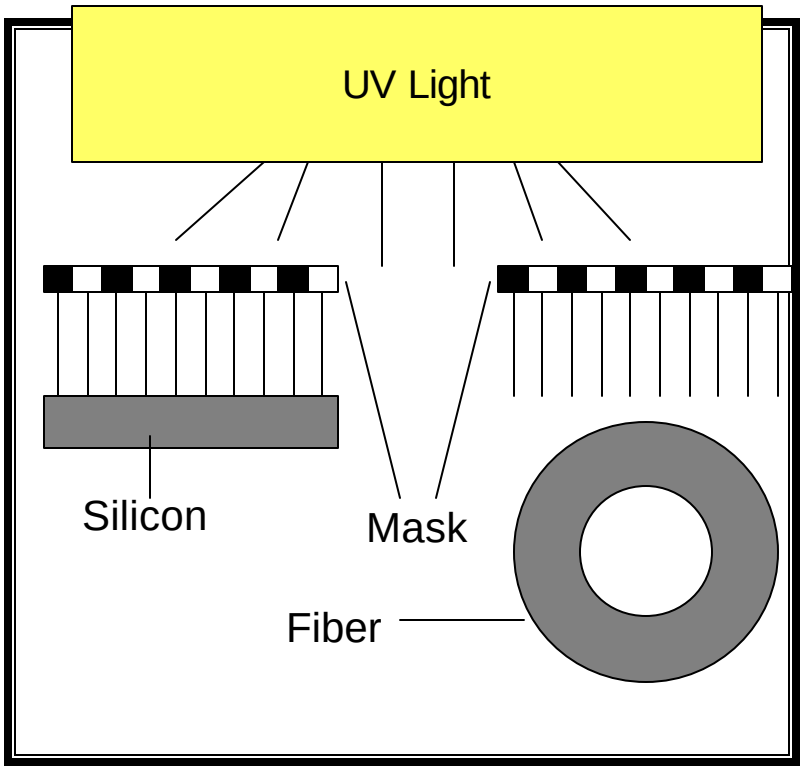
- **Bad patterns due to large gap between fiber and metal sheet**
- **Modification applied – sidewall of slot inclined to minimize gap by contact with fiber (analogous to contact lithography)**



UV Light



Challenges of Device/Sensor Fabrication on Fibers



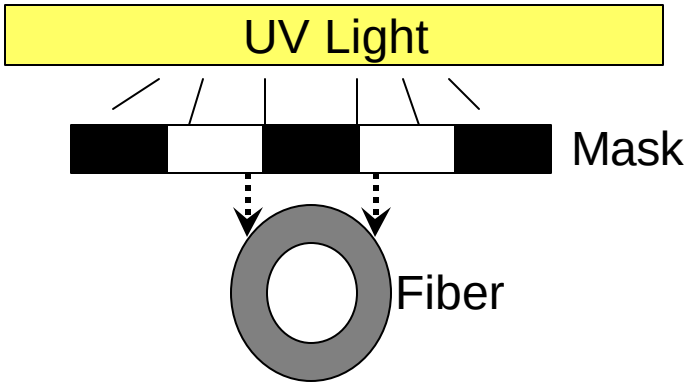
- **Masking**
  - To use entire surface area for patterning
  - Standard mask – flat
- **Lithography**
  - To obtain accurate pattern transfer on curved surfaces
  - Non-uniform exposure due to curved shape of fiber
- **Metal Deposition and Lift-off**
  - Accuracy will prevent adhesion problems due to shape of substrate

SOLUTION

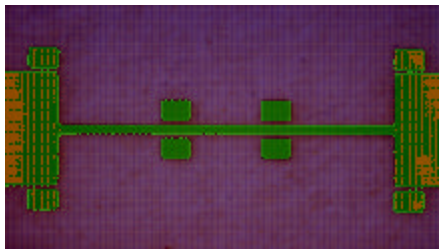
- **Desired mask – cylindrical**

Cylindrical vs. Flat Mask Geometry

Standard flat mask

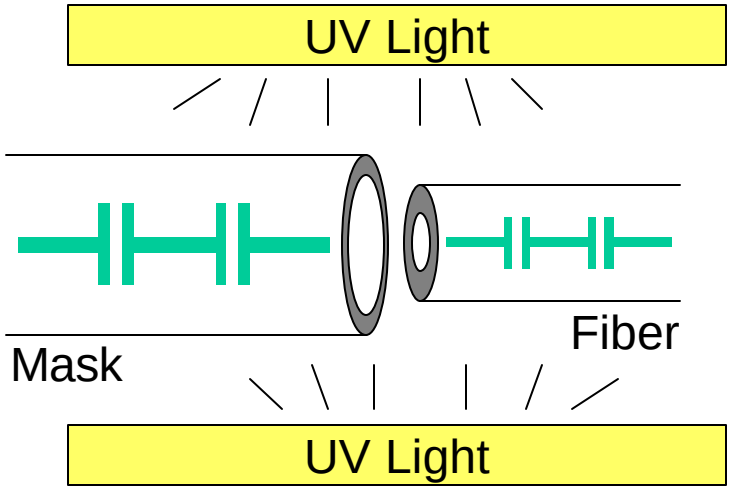


- Used in standard microfabrication procedures
- Use of less surface area
- Curved structure – distorted images



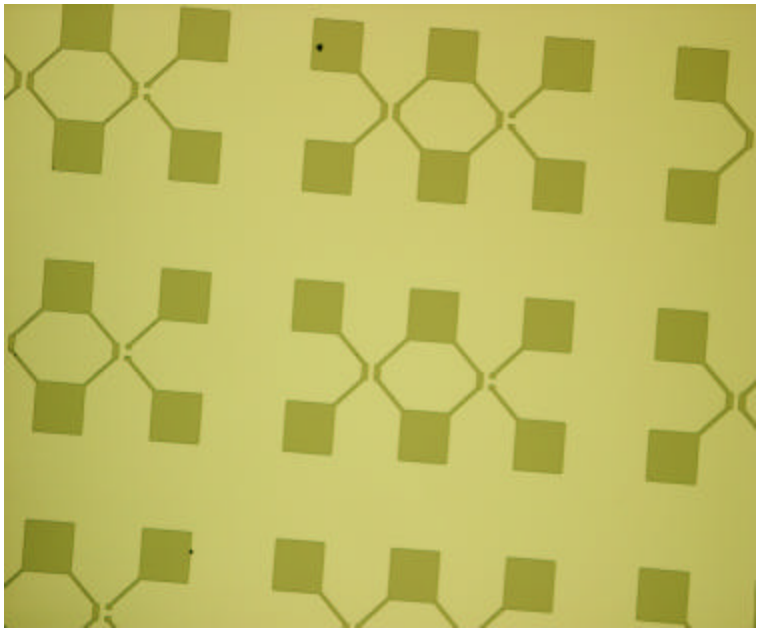
Standard Flat Mask Plate

Cylindrical mask

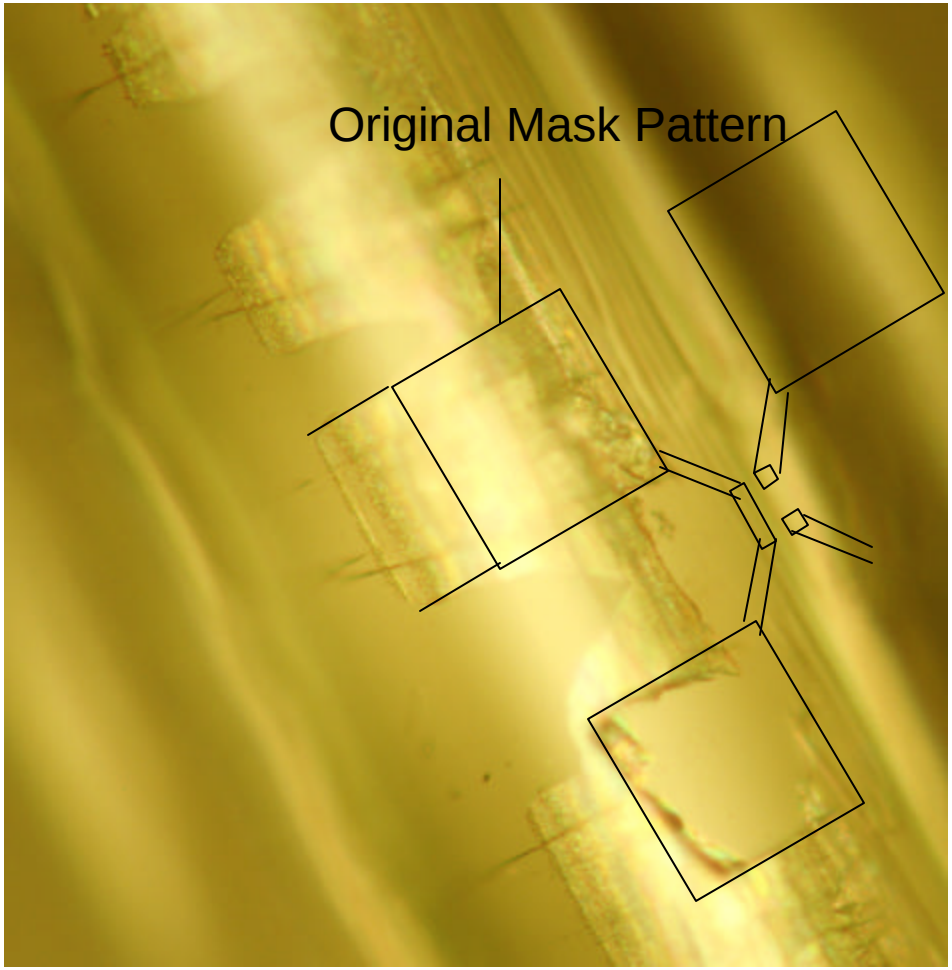


- Curve of mask corresponds to curve of substrate (fiber)
- Distortion of images reduced
- More uniform UV exposure
- Covers complete surface area

Example of Flat Mask Pattern



Applied mask pattern



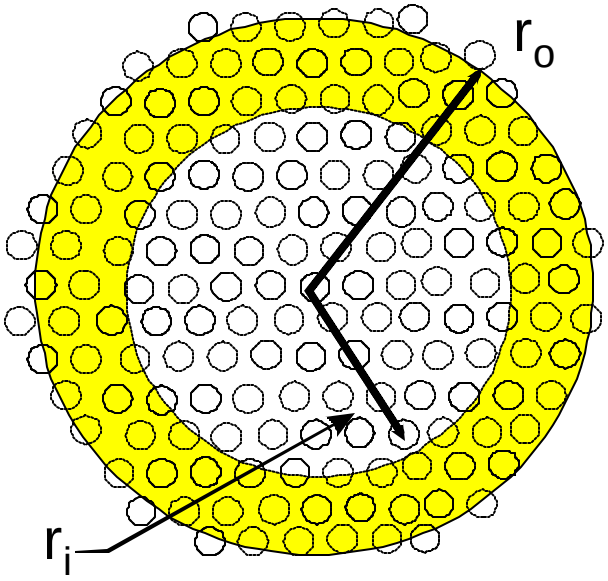
Proven that traces can applied to fibers, but distorted pattern due to flat mask
Solution: Cylindrical mask

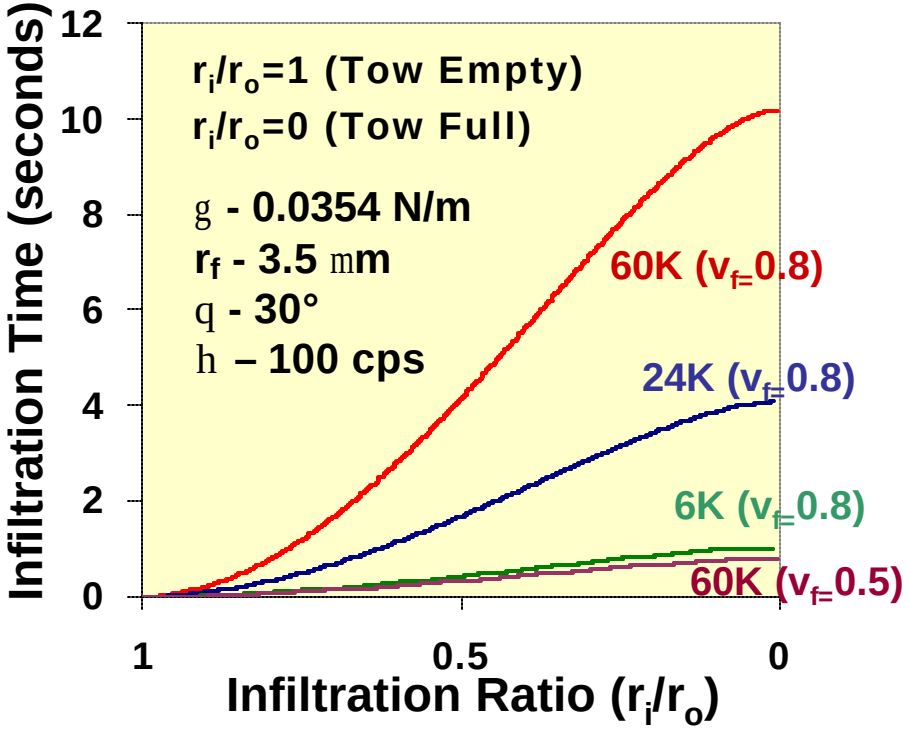
Sensor Design and Development

- **Three basic sensor designs developed**
  - Flow monitoring
  - Temperature sensing
  - Strain sensing
- **Issues with sensors on fiber**
  - Reliability of device/sensor
  - Multiple connectors and traces required for measurements
- **Advantages**
  - Monitoring of Micro-Flow or local parameters (millimeter size) possible
  - Creation of “smart” composites

Flow Monitoring

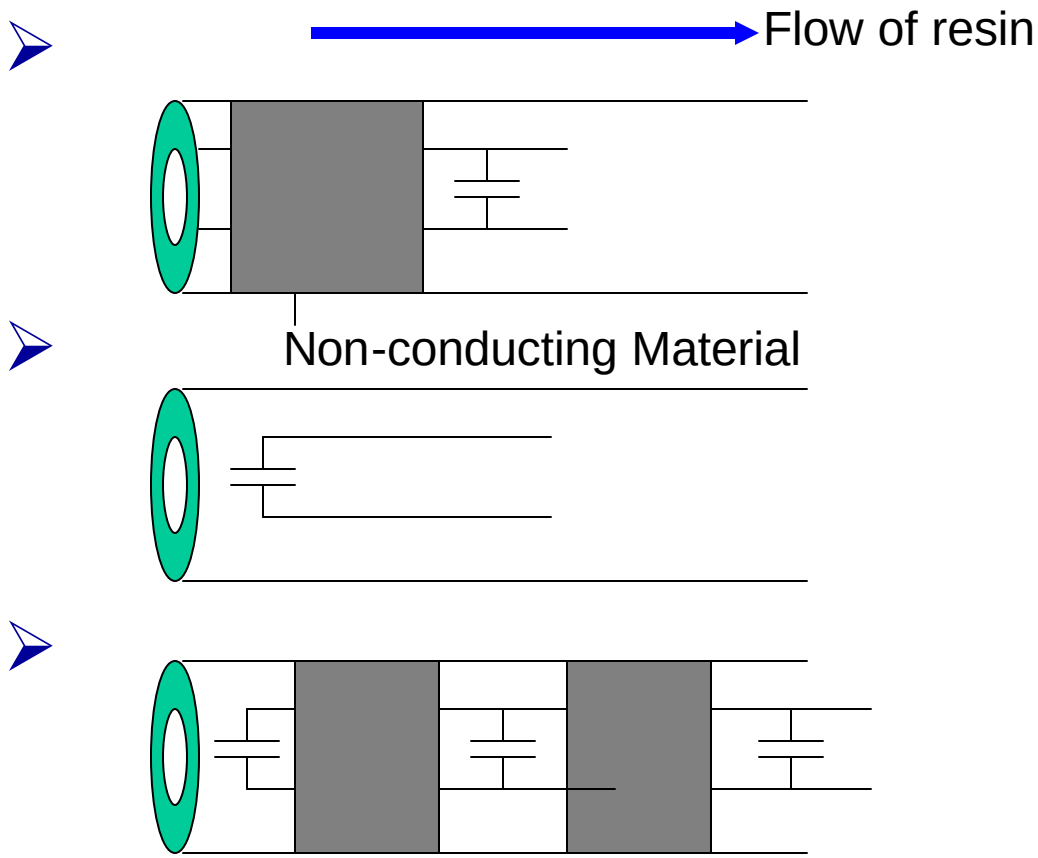
- **Basic idea**
  - To detect position of resin within fiber tow
- **Validation of Micro-Flow Models**
  - Flow path of resin to fiber
  - State in between wet and dry stages of fiber



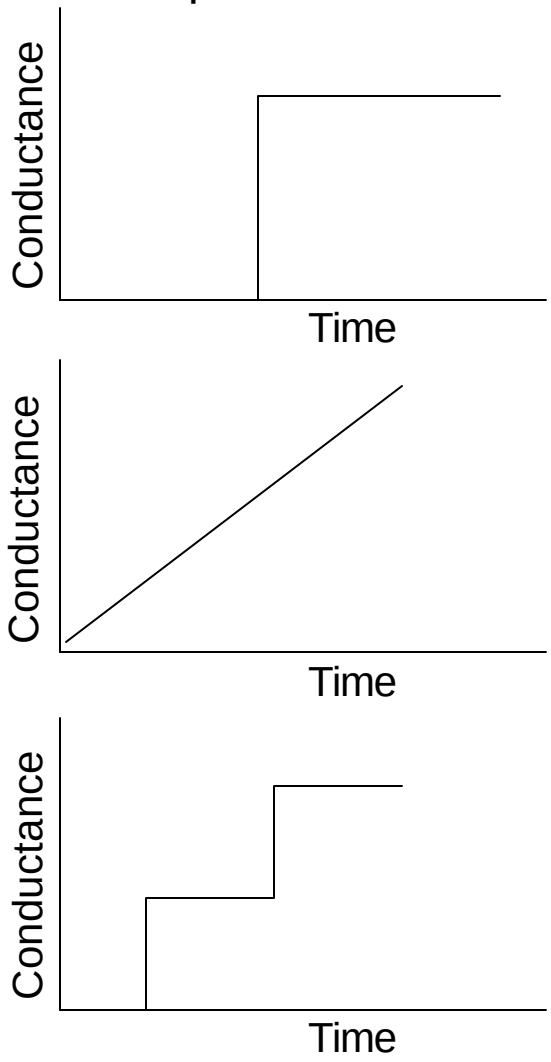


Flow Monitoring

Preliminary designs



Anticipated relations

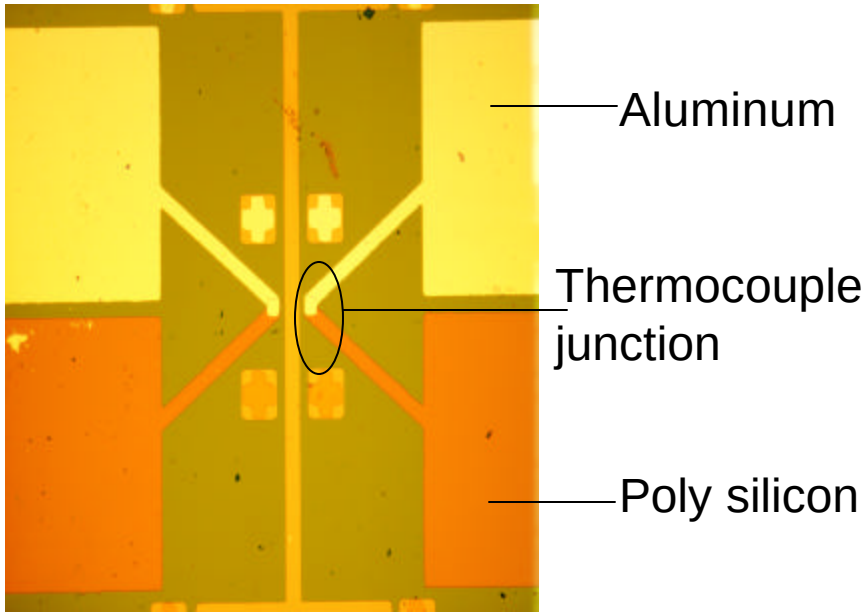


Thermocouple Temperature Sensor

- **Example of thermocouple temperature sensor**
  - **Si-Al thermocouple junction**
  - **Seebeck Coefficient of Polysilicon (S_1): -415.6 μV/K)**
  - **Seebeck Coefficient of Aluminum (S_2): -1.7 μV/K**

$$V = \int_{T_1}^{T_2} [S_1(T) - S_2(T)] dT$$

  - **Sensitivity increased by increasing the number of elements**



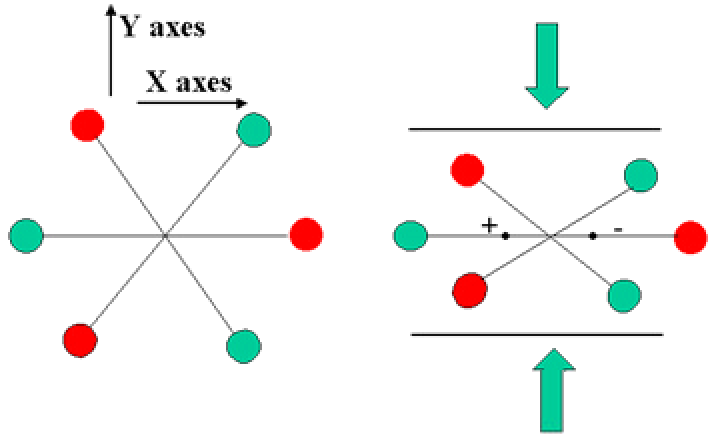
- **Application: monitoring local exothermic reactions (micro-kinetics)**

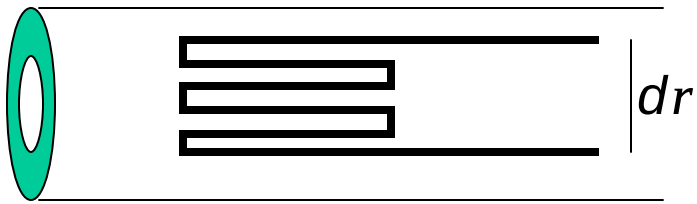
Strain Sensor Concept

- **Theory behind piezoelectricity**
  - Mechanical stress applied on materials with non-centro symmetric crystallinity induces formation of dipoles
- **Piezoresistivity**
  - Change in resistance due to strain
  - Gauge factor:

$$k = \frac{dr}{r}$$

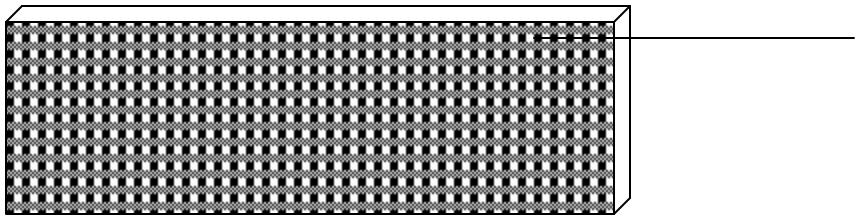
  - $r \rightarrow$ intrinsic resisitivity of material
- **Application**
  - Residual stress measurement
  - Health monitoring of composite
  - Vibration measurement





Long Term Objectives

- **Automated process to make Smart Preforms of fiber-based sensors**

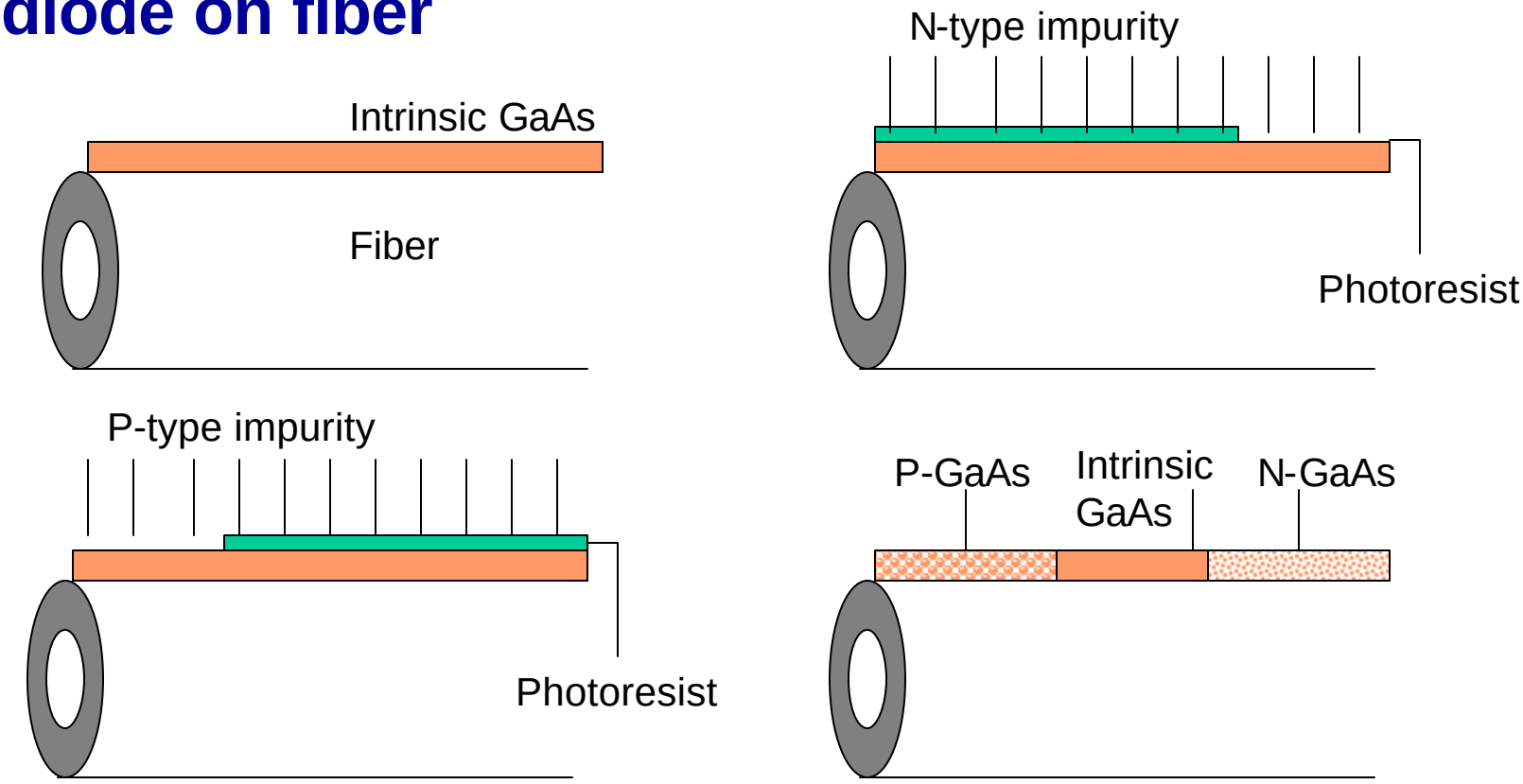


Sensors embedded within preform continuously generating and transmitting data

- **Electronic devices on fibers to make circuits**
  - **Diodes**
  - **Transistors**
  - **Microprocessors!**

Example – Diode Fabrication

- **Simplified procedure of fabricating a GaAS P-I-N diode on fiber**



Summary

- Preliminary research on sensors/devices on fibers
- Key hurdles
  - Circular masks
  - Connection to the outside world
- Evaluated photo-resist materials and developed continuous application process
- Applied successful flat mask pattern on fiber
- Developed design concepts for sensors